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Searches for Second Generation Leptoquarks in the mmjj channel

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Abstract

We report on a search for second generation scalar leptoquarks, done using 126 pb^{-1} of run II data taken at $\sqrt{s}$ = 1960 GeV . Leptoquarks are assumed to be pair produced and to decay into a lepton and a quark of the same generation. We will focus on the signature represented by two energetic muons and two jets. We set an upper limit at 95% CL on the production cross section as a function of the mass of the leptoquark. By Assuming ($\beta = Br(LQ \rightarrow \mu q)) = 1$ and using the NLO theoretical estimate we reject the existence of scalar leptoquarks with mass below 206 GeV/c^2.

Introduction

Leptoquarks are hypothetical color-triplet particles carrying both baryon and lepton quantum numbers and are predicted by many extension of the Standard Model as new bosons coupling to a lepton-quark pair[1]. Their masses are not predicted. They can be scalar particles (spin 0) or vector (spin 1) and at high-energy hadron colliders they would be produced directly in pairs, mainly through gluon fusion or quark antiquarks annihilation. In figure 1 a typical production diagram is reported.

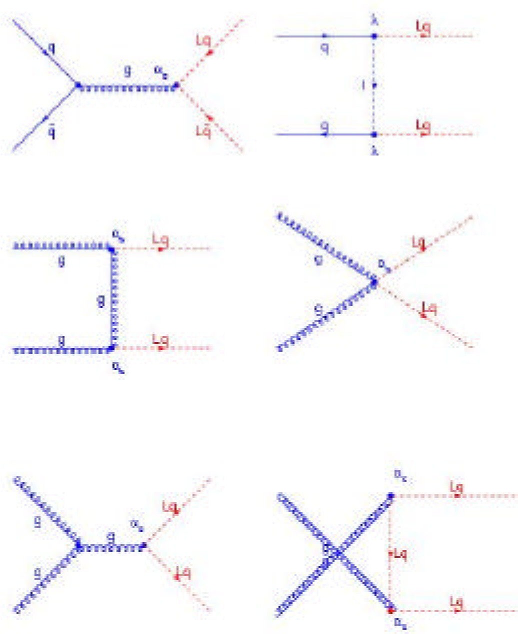

Figure 1

The couplings of the leptoquarks to the gauge sector are predicted due to the gauge symmetries, up to eventual anomalous coupling in the case of vector leptoquarks, whereas the fermionic couplings λ are free parameters of the models. In most models leptoquarks are expected to couple only to fermions of the same generations because of experimental constraints as non-observation of flavor changing neutral currents or helicity suppressed decays. The production cross section for pair produced scalar LQ has been calculated up to NLO[1].The decay angular distribution of scalar leptoquarks is isotropical. The NLO cross section at $\sqrt{s}$ = 1960 GeV is reported in Table 1 for values of the LQ mass between 200 and 320 GeV/c^2. The scale has been chosen to be $Q^2 = M_{LQ}^2$ and the set of parton distribution functions is CTEQ4M[].

M_{LQ} (GeV/c^2)	σ(NLO) [pb]
200	0.265E+00
220	0.139E+00
240	0.749E-01
260	0.412E-01
280	0.229E-01
300	0.129E-01
320	0.727E-02

Table 1

The cross section compared with the one at 1.8 TeV is reported in Figure 2

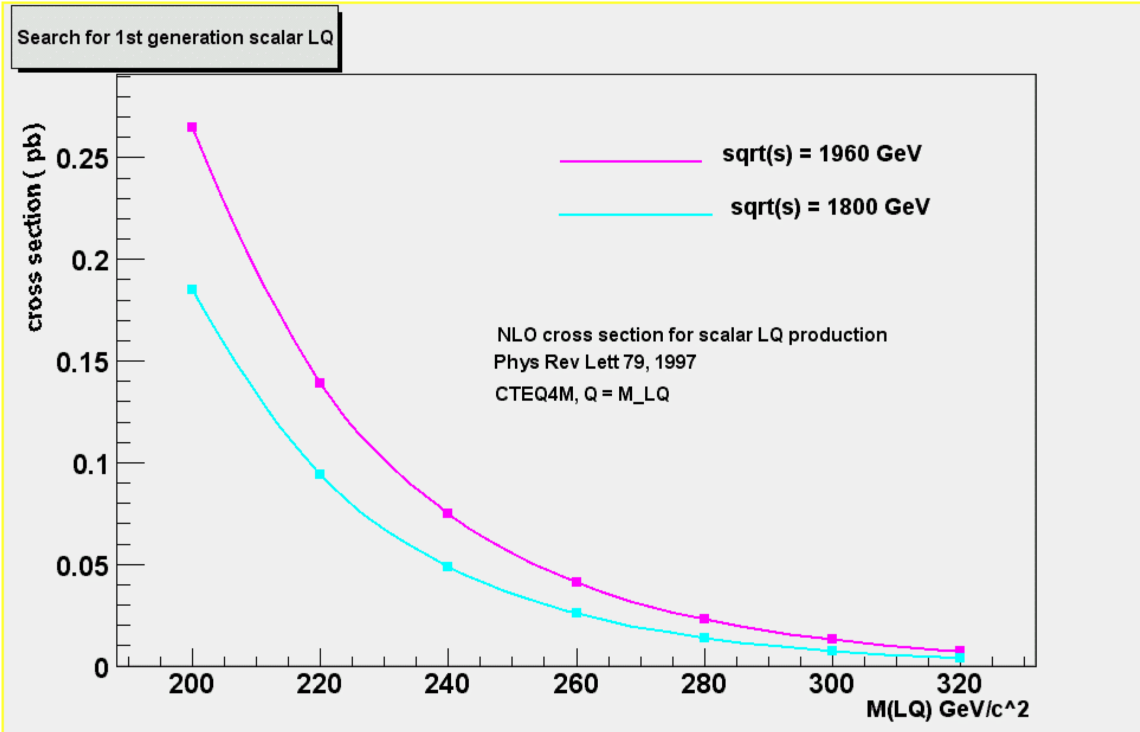

Figure 2

This analysis is focused on the search for second-generation scalar leptoquarks, pair produced and decaying into μμjj. The analysis strategy is following closely the one adopted in the search for first generation leptoquarks, carried out in Winter 2003[2].

Current Limits

In table 1 the current limits on the first generation LQ are reported, both from CDF and D0.

1^{st} Gen	β	Scalar (GeV/c^2)
D0	1	186 (Run II)
	1	200(Run I)
	0.5	180 (Run I)
CDF	1	202 (Run I)
	0	105 (Run II)

Table 2 – current limits on second generation LQ from the TeVatron

Data sample and muon identification

The data sample used for this analysis is *btop1g/j* (inclusive muons) stripped for the Top group from the inclusive high pt muon datasets. The sample is described in[4]. For the triggered muons, we use the full central muon detector, which is composed of three parts: CMU, CMP and CMX. The L3 trigger names are MUON_CMUP18 MUON_CMX18.
The L3 trigger dataset *(bhmu08/09*) was reconstructed with offline version 4.8.4 and the events were filtered into *btop01g/j* using the following loose cuts:

- minPtCut set 18.0
- useSlidingEmCut set true
- useSlidingHadCut set true

- maxCMUdXCut set 5.0
- maxCMPdXCut set 10.0
- maxCMXdXCut set 20.0
- maxBMUdXCut set 50.0

A REMAKE version of *b0topg* was made with software version 4.11.1 where all the calorimeter-dependent objects were dropped in input as well as electron and muon reconstruction objects. The 4.8.4 tracks were refitted (using TrackRefitModule) without L00 hits, and electron and muon objects were remade picking up the refit tracks and run-dependent calorimeter corrections. The sample is on caf disks in *fcdfdata013.fnal.gov//cdf/scratch/cdfdata/top/results/Inclusive-muo_4104_REMAKE_** and corresponds to an integrated luminosity of 126 ± 8 pb^{-1} (good runs between March 23 2002 to May 2003 – runs 141544 to 163527, selected following the *good run list without Silicon* used by the Top group for Summer conferences, available at: http://www-cdf.fnal.gov/internal/physics/top/RunIIWjets/summer03data/goodrun/old/goodrun_nosi.list).
For the CMX detector, the good run list is divided in two sections, pre-CMX and post-CMX. This leaves us with $L_{pre\text{-}CMX}$ = 16 pb^{-1} and $L_{post\text{-}CMX}$ =110 pb^{-1} .

The sample has been reduced by requiring events with at least 2 muons of type CMU,CMP or CMX satisfying the criteria outlined in Table 2. The possible dimuon combinations are the following three:

- CMUP-CMUP where both the muons pass the selection criteria for a CMUP muon;

- CMX-CMX where both the muons pass the selection criteria for a CMX muon. A CMX muon is also request to pass the COT exit radius requirement;
- CMX-CMUP where one muon passes the CMUP identification criteria and the other passes CMX.

The muon identification cuts are also used in the Z' [4,5] analysis and the efficiencies are reported in Table 3. The muon offline group has recently proposed the exit radius cut. It is a similar approach as in Run I to label a CMX muon correctly. Due to the trigger design, the trigger acceptance is not the same as the detector acceptance. The effect of the cut is of correct the acceptance (lowering it) and the trigger efficiency (raise it) of the CMX muon.

To remove cosmic rays contaminating the sample the di-cosmic bit is used, which is based on the use of the COT timing information to deduce if the muons are compatible with an outgoing pair as one would expect in a physics process. The bit is taken from the cosmic bit word stored in the CosmicRayTaggerInfo object.

DefTracks are used in this analysis.

Cut Variable	Purpose	Type	Condition
L1,L2 & L3	Enforce trigger	trigger	CMUP or CMX bit on
p_T	High p_T muon	Trigger,kinematic	>20 GeV (DefTracks)
Δx (CMU)(if CMUP)	Track-stub match	ID	<3 cm
Δx (CMP)(if CMUP)	Track-stub match	ID	<5 cm
Δx (CMX)(if CMX)	Track-stub match	ID	<6 cm
E_{em} (sliding)	MIP	ID	<2 GeV, <2+0.0115*(p-100) for p>100 GeV
E_{had}(sliding)	MIP	ID	<6 GeV, <6+0.0280*(p-100) for p>100 GeV
Dicosmic bit	Cosmic ray rejection	Background rejection	on
$I_{0,4}$ fractional isolation	QCD rejection	Background rejection	< 0.1*p_T

Table 2: Muon selection cuts

	CMUP	CMX
$e_{\mathbf{trig}}$	87.6 ±1.3%	97.7 ±0.6%
$e_{\mathbf{fid}}$	95.1 ±0.1(stat) ±0.5(sys) %	95.1 ±0.1(stat) ±0.5(sys) %
$e_{\mathbf{muID}}$	91.3±0.5%	95.7 ±0.5%
$e_{\mathbf{muReco}}$	92.7 ±0.3(sys) ±1.0(stat) %	99.2 ±0.3(sys) ±1.1(stat) %
$e_{\mathbf{muIso}}$	97.4 ±0.3%	98.2 ±0.3%

Table 3 – Efficiency summary table as from ref[4,5]

Difference with the Run I analysis

In Run I an analysis searching for second generation LQ decaying 100% into μ jet was carried out[10]. The analysis was selecting 2 muons, one tight CMUO and one tight CMUO *or* loose CMIO, defined as a track without an associated stub and with no fiducial requirement. This already increases the geometrical + P_t cut acceptance of about 30% (almost 50% for LQ of 240 GeV/c^2) as in the present analysis we make use of only tight CMUP and CMX muons:

Mass (GeV/c^2)	Run I (pt>20)	Run II (pt>25)
200	0.475 (0.34, 0.14)	0.306
220	0.477 (0.34, 0.14)	0.307
240	0.488 (0.35, 0.14)	0.32

The final efficiencies are higher at these masses of basically the same amount (the LQ mass constrain is used instead of the kinematical cuts used in the present analysis) and considering the differences between trigger/ID/reconstruction efficiencies used in the 2 analysis.

Mass (GeV/c^2)	Run I (pt>20)	Run II (pt>25)
200	0.204	0.12
220	0.212	0.13
240	0.218	0.14

this difference balances out the cross section difference and luminosity difference with the present analysis, and, as we will see will allow us to get a comparable result. It is in our plans to make use of stubless muons as well to increase the geometrical acceptance.

Acceptance and kinematical efficiency calculation

We generated 5000 events samples of scalar leptoquarks pair decaying into *mq* for M_{LQ} in the range 160 to 320 GeV/c^2 using Pythia[10]. The samples have been generated to simulate realistic beam conditions, emulating run number 151435 and using the following talk-to for the full beam position:

```
talk GenPrimVert
BeamlineFromDB set false
 sigma_x       set  0.0025
  sigma_y       set  0.0025
  sigma_z       set 28.0
  pv_central_x   set -0.064
  pv_central_y   set  0.310
  pv_central_z   set  2.5
  pv_slope_dxdz  set -0.00021
  pv_slope_dydz  set  0.00031
exit
```

The samples were generated with $Q^2 = M_{LQ}^2$ and the MRS-R2 pdf set[12]. The samples were simulated with cdfSim version 4.9.1 and Production 4.9.1 was ran on them.
In figure 3-5 some distributions from the decay products of the Leptoquark are plotted, for a leptoquark mass of 220 GeV/c^2, after reconstruction.

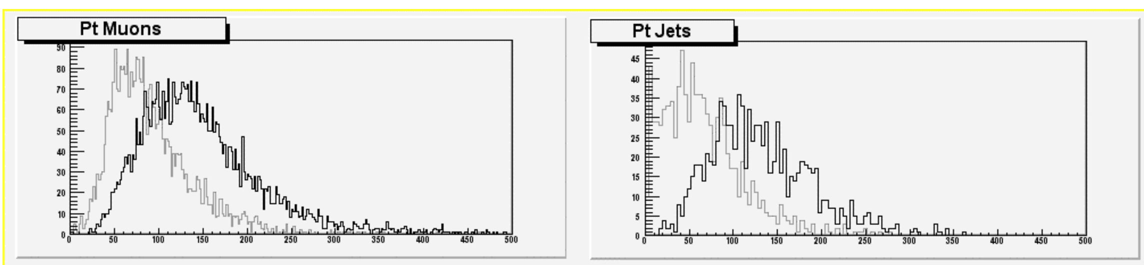

Figure 3 – P_T and E_T distributions for muons and jets for m(LQ) = 220 GeV/c^2

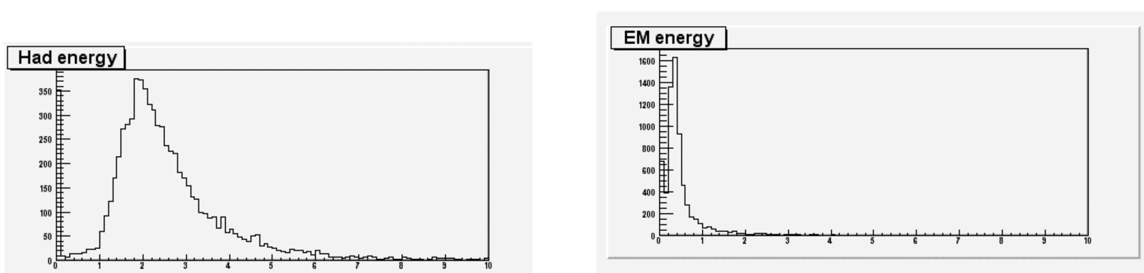

Figure 4 – E_{em} and E_{had} for muons from LQ decay (m(LQ) = 220 GeV/c^2)

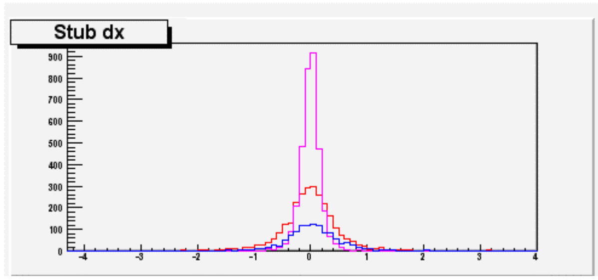

Figure 5 – Stub-track matching for various muons types

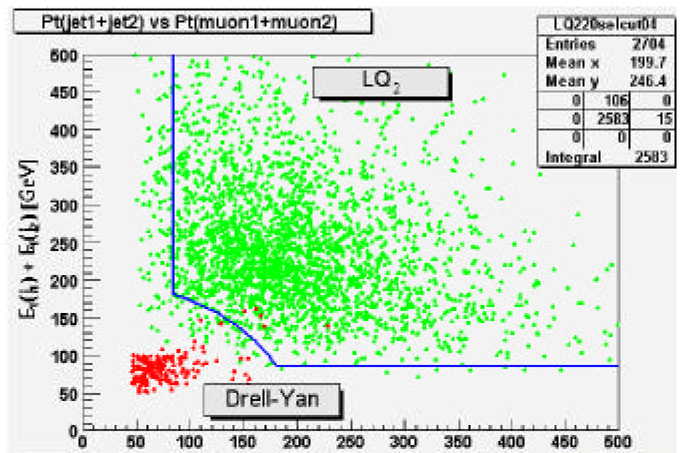

Figure 6 - Sum of E_T(jets) vs Sum of P_T(muons)

We apply the following kinematical cuts:

- 2 muons with $P_T > 25$ GeV
- 2 jets with $E_T(j1) > 30$ and $E_T(j1) > 15$ GeV
- Removal of events with $76 < M_{\mu\mu} < 110$ and $M_{\mu\mu} > 15$ GeV/c^2
- $E_T(j1) + E_T(j2) > 85$ GeV && $E_T(\mu1) + E_T(\mu2) > 85$ GeV
- $\sqrt{((E_T(j1) + E_T(j2))^2 + (E_T(\mu1) + E_T(\mu2))^2)} > 200$ GeV

The last cut was shown in the search for 1st generation LQ to discriminate between signal and background, as shown in Figure 6, where the sum of the muon P_T is plotted against the sum of the 2 jets E_T for signal, DY + 2 jets after selecting 2 muons and 2 jets.

The analysis cuts efficiencies are calculated relatively to the number of events having 2 muons matching the generator level muons, while the geometrical acceptance is taken into account when selecting events with only muons of type CMUP or CMX. They are reported in Figure 8 and Table 4. The efficiencies are then folded with muon ID efficiencies reported in Table 2, z vertex cut efficiency[7] (fiduciality), trigger efficiency[9] , muon reconstruction efficiencies and fractional isolation cut efficiency. We have verified that the muon identification efficiencies for 2 CMUP/CMX muons for the signal (M_{LQ} = 240 GeV/c^2) are of the same order of magnitude of the ones calculated from real Z data.

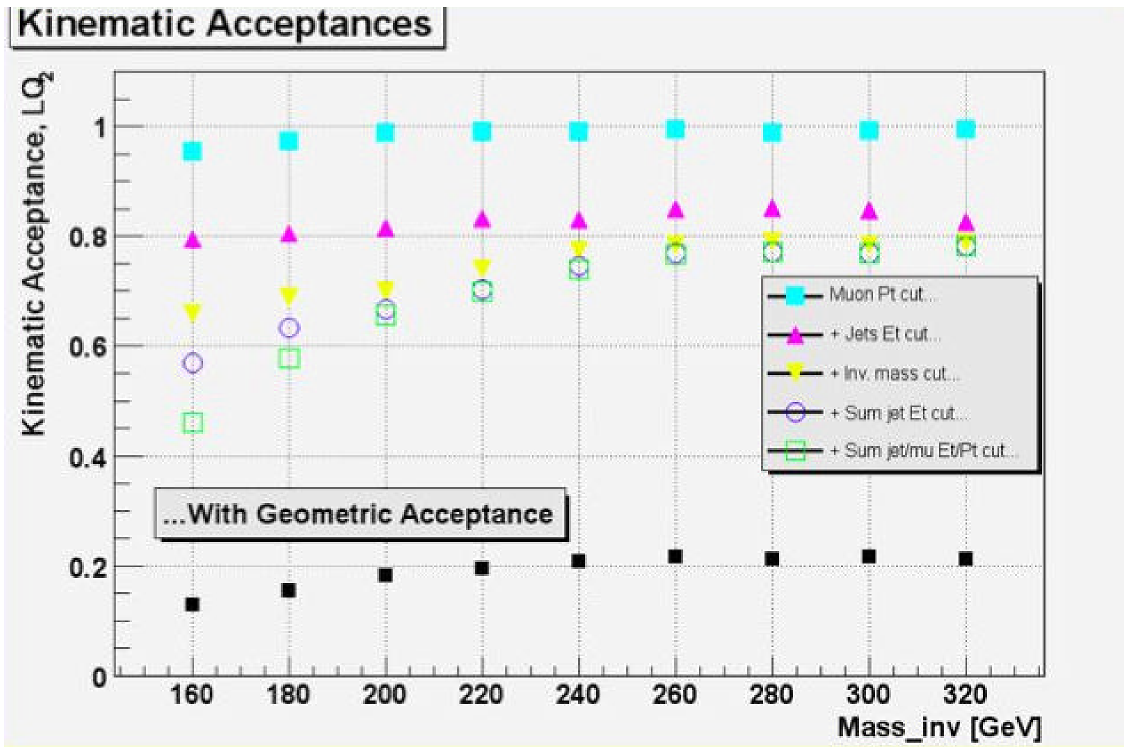

Figure 8 – kinematical efficiency as function of the leptoquark mass

Mass (GeV/c^2)	CMUP/CMUP	CMUP/ CMX	CMX / CMX	TOTAL
160	**0.047± 0.001 ± 0.003**	**0.034 ± 0.00±0.003**	**0.006 ±0.001±0.001**	**0.087 ±0.002 ±0.007**
180	**0.057± 0.002 ± 0.004**	**0.04 ± 0.01 ±0.01**	**0.007 ±0.001 ±0.001**	**0.105 ±0.003 ±0.008**
200	**0.068 ± .002±0.005**	**0.048± 0.001± 0.003**	**0.007±0.001 ± 0.005**	**0.124 ± 0.003 ± 0.009**
220	**0.063 ±0.002±0.005**	**0.061± 0.001± 0.004**	**0.010± 0.002 ± 0.001**	**0.135 ± 0.003 ± 0.01**
240	**0.074±0.002± 0.006**	**0.056± 0.001± 0.004**	**0.012± 0.001 ± 0.001**	**0.142± 0.004 ± 0.012**
260	**0.08 ±0.002 ± 0.006**	**0.056± 0.001± 0.004**	**0.011±0.0002± 0.001**	**0.147 ± 0.004 ± 0.010**
280	**0.077 ±0.002±0.006**	**0.056± 0.001± 0.004**	**0.011± 0.001 ± 0.001**	**0.145± 0.003± 0.011**
300	**0.079± 0.002±0.006**	**0.060± 0.002± 0.004**	**0.009± 0.001±0.001**	**0.147 ± 40.003 ± 0.011**
320	**0.080 ± 0.002±0.006**	**0.054± 0.001± 0.004**	**0.011± 0.001± 0.001**	**0.144 ± 0.004 ± 0.011**

Table 4 - kinematical efficiency as function of the leptoquark mass

The expected number of events of signal in 126 pb^{-1} given the above efficiencies and the NLO theoretical cross section for different value of the renormalization/factorization scale, is reported in the Table below:

Mass (GeV/c^2)	n Theory CTEQ4M (pb) $Q^2 = M^2_{LQ}/4$	n Theory CTEQ4M (pb) $Q^2 = 4M^2_{LQ}$
160	13.11	10.44
180	7.54	6.05
200	4.48	3.62
220	2.56	2.06
240	1.45	1.17
260	0.84	0.67
280	0.46	0.36
300	0.26	0.21
320	0.15	0.12

Table 5 – Expected number of signal events in 126 pb^{-1}

After our selection cuts 0 events are left. In Table 6 we report the number of events surviving each kinematical cut.

Number of events with 2 muons with $P_T > 25$ GeV	1561
2 jets with $E_T(j1) > 30$ GeV and $E_T(j1) > 15$ GeV	15
removal of events with $76 < M_{\mu\mu} < 110$ GeV/c^2 and $M_{\mu\mu} > 15$ GeV/c^2	4
$E_T(j1) + E_T(j2) > 85$ GeV && $E_T(\mu1) + E_T(\mu2) > 85$ GeV	1
Ö$((E_T(j1) + E_T(j2))^2 + (E_T(\mu1) + E_T(\mu2))^2) > 200$ GeV	0

Table 6 – List of events passing the selection cuts

Backgrounds

The main backgrounds is due to $\gamma/Z\to\mu\mu$ events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on $M_{\mu\mu}$ around the mass of the Z boson and the ΣE_T cuts. However there are still events from the DY continuum and Z events that fail the cuts due to mis-measurement. We studied the distribution of this background by generating the process Z + 2 jets with Alpgen[11] and using the MC parton generator mcfm[13] to obtain the NLO cross section.
Another source of background is represented by tt production where both the W decay into $\mu\nu$. Other backgrounds from bb, $Z\to\tau\tau$, WW are expected to be negligible due to the the isolation cut and large muon and jet transverse energy/p_T requirements. The expected number of DY + 2 jets events in 126 pb^{-1} is 0.351 ± 0.022. The expected number of tt events is 0.089 ± 0.01 events. To normalize simulated events to data we used the theoretical cross section for tt, $\sigma(tt)\times Br(W\to\mu\nu) = 0.0739$ pb, and the theoretical cross section for Z/γ + 2 jets at NLO accuracy as calculated with the mcfm MC program.

The total number of expected events of background is 0.44 ± 0.04.

We also checked that the events we are left before requiring the jets and the following analysis cuts are consistent with the production of Z.
Z boson candidates are selected by requiring 80 GeV $< M_{\mu\mu} < 100$ GeV/c^2 (as in the Z' analysis) and the cross section is calculated from the following formula:

$$s \times Br\,(pp\to Z \to\mu\mu) = (N_Z - N_{BG})/(A_Z\times\varepsilon_{\mu\mu}\times L)$$

Using the values listed in the Table 6 we obtain for the Z cross section values compatible with other measurements.

	CMUP-CMUP	CMX-CMX	CMUP-CMX
Acceptance (from Z' analysis)	0.027 ± 0.001	0.0076 ± 0.001	0.027 ± 0.001
Acceptance (from Z +2 jets MC)	0.033 ± 0.0004	0.010 ± 0.001	0.037 ± 0.001
ID/reco/Trigger/vertex efficiencies	0.63 ± 0.02	0.826 ± 0.02	0.73 ± 0.02
Observed number of events	**566**	**157**	**540**
Estimated background	0.3 ± 0.0	0.5 ± 0.0	0.65 ± 0.0
Integrated Luminosity (pb^{-1})	126 ± 7.7	110 ± 6.6	110 ± 6.6
Cross Section (pb)	264.1 ± 19.5	227.4 ± 15.2	249.6 ± 20.5

Table 6 – parameters used in the calculation of the Z cross section

Systematic Uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%
- Acceptance
    - pdf 4.3% (from run I)
    - statistical error of MC 2.2%
    - Jet energy scale < 1%
- Muon ID efficiency[5,6]
    - muon reconstruction: 0.3%
- Event vertex cut : 0.5%[7]

Adding the above systematic uncertainty in quadrature will give a total systematic uncertainty of about 8%.

Mass	**A**(M_{LQ})		**statistical**		**systematic**	**combined (rel)**
160	0.087581	+/-	0.00224182	+/-	0.0070664	0.0846869
180	0.105062	+/-	0.00269242	+/-	0.0080473	0.080798
200	0.123776	+/-	0.00317889	+/-	0.0093412	0.080798
220	0.134753	+/-	0.00341278	+/-	0.0100800	0.0797452
240	0.142546	+/-	0.00363111	+/-	0.0106474	0.0790027
260	0.147573	+/-	0.00377578	+/-	0.0109909	0.0789498
280	0.144691	+/-	0.00369249	+/-	0.0107928	0.0788671
300	0.147535	+/-	0.00377653	+/-	0.0109724	0.0786805
320	0.144502	+/-	0.00369754	+/-	0.0107424	0.0786514

Figure 9 – final acceptances and errors

Cross section Limit

The production cross section σ of the process LQLQ$\rightarrow$ $\mu\mu$jj can be written as follows:

$$\sigma\times Br(LQLQ\rightarrow \mu\mu jj) = \sigma\times\beta^2 = N/(\varepsilon\times L),$$

where N is the number of observed events on data after our selection, ε is the total selection efficiency as a function of M_{LQ} and L is the integrated luminosity. As we found no candidate events in our selection, we set a 95% C.L. upper limit on the cross section as a function of M_{LQ} defined as:

$$\sigma^{lim} = N^{lim}/(\varepsilon\times L\times\beta^2)$$

The limit was calculated using bayes[14].
In Table 7 we report the values of the limit cross sections in $\mu\mu$jj for each M_{LQ} and for β = 1 and the theoretical calculations at NLO for pair production of scalar LeptoQuarks at the TeVatron done using CTEQ4M pdf and for different choices of the scale.In Figure 10 the limit cross-section as function of M_{LQ} is compared with the theoretical expectations for β = 1. At the intersection point between experimental and theoretical curves we find the lower limit on M_{LQ} at 206 GeV/c^2.

Mass (GeV/c^2)	95%CL σ (pb)	σ Theory CTEQ4M (pb) $Q^2 = M^2_{LQ}/4$	σ Theory CTEQ4M (pb) $Q^2 = 4M^2_{LQ}$
160	0.27	1.19	0.948
180	0.23	0.571	0.458
200	0.19	0.288	0.233
220	0.180	0.151	0.122
240	0.17	0.08	0.065
260	0.167	0.045	0.036
280	0.164	0.025	0.02
300	0. 164	0.014	0.011
320	0.168	0.008	0.007

Table 7 – *Values of the upper limits at 95% CL of the production cross section of second generation leptoquarks decaying into mmjj channel as a function of M_{LQ}. The last 2 columns on the right report the result of the theoretical calculations at Next-To-Leading order with CTEQ4M for different choices of the scale, multiplied by a factor b´b = 1.*

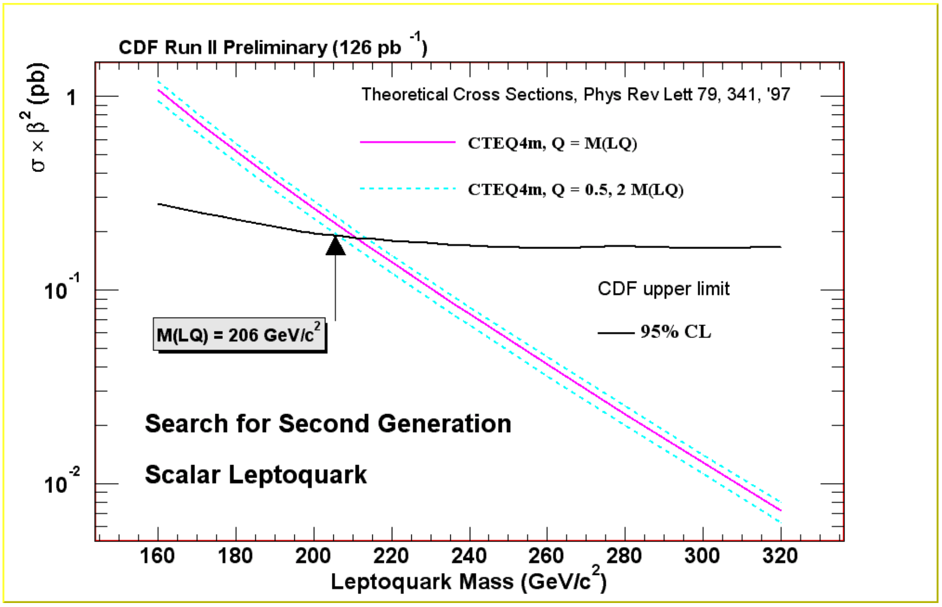

Figure 8 - *Limit cross section as a function of M_{LQ} compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M_{LQ} at 206 GeV/c^2*

Conclusions

We have presented a preliminary 95% CL cross section lower limit as a function of M_{LQ}, for leptoquarks decaying with 100% branching ratio into μq and we have compared it to the theoretical predictions for leptoquark pairs production at the TeVatron. By using the theoretical estimate, we can reject the existence of a scalar leptoquark with mass lower than 206 GeV/c^2 for $\beta = 1$.

Acknowledgements

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